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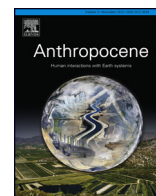
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## Land system science and sustainable development of the earth system: A global land project perspective



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### ABSTRACT

Land systems are the result of human interactions with the natural environment. Understanding the drivers, state, trends and impacts of different land systems on social and natural processes helps to reveal how changes in the land system affect the functioning of the socio-ecological system as a whole and the tradeoff these changes may represent. The Global Land Project has led advances by synthesizing land systems research across different scales and providing concepts to further understand the feedbacks between social and environmental systems, between urban and rural environments and between distant world regions. Land system science has moved from a focus on observation of change and understanding the drivers of these changes to a focus on using this understanding to design sustainable transformations through stakeholder engagement and through the concept of land governance. As land use can be seen as the largest geo-engineering project in which mankind has engaged, land system science can act as a platform for integration of insights from different disciplines and for translation of knowledge into action.

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### 1. Introduction

Land systems constitute the terrestrial component of the Earth system and encompass all processes and activities related to the human use of land, including socioeconomic, technological and

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organizational investments and arrangements, as well as the benefits gained from land and the unintended social and ecological outcomes of societal activities (Verburg et al., 2013). Changes in land systems have large consequences for the local environment and human well-being and are at the same time pervasive factors of global environmental change. Land provides vital resources to society, such as food, fuel, fibres and many other ecosystem services that support production functions, regulate risks of natural hazards, or provide cultural and spiritual services. By using the land, society alters and modifies the quantity and quality of the provision of these services.

Land system changes are the direct result of human decision making at multiple scales ranging from local land owners decisions to national scale land use planning and global trade agreements. The aggregate impact of many local land system changes has far reaching consequences for the Earth System that feedback on ecosystem services, human well-being and decision making (Crossman et al., 2013). As a consequence, land system change is both a cause and consequence of socio-ecological processes.

The land system science community is organised through the Global Land Project (GLP). The orientation of land system science at the interface of social, physical and ecological systems is reflected by the origin of GLP, which, until the transition to Future Earth, was a core project of both the International Geosphere Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP) commissioned by the International Council for Science (ICSU) and the International Social Science Council (ISSC). The Global Land Project started in 2006 after publishing its science plan in 2005 (GLP, 2005). GLP is a successor of the previous Land Use and Land Cover Change project (LUCC; 1994–2005) and the Global Change and Terrestrial Ecosystems project (GCTE; 1992–2003). GLP aims at synthesis and integration of insights, knowledge and methodologies in research across the land system science community. A core task of GLP is the identification of scientific priorities and agenda setting through synthesis of existing knowledge, meta-analysis of land-based research and targeted workshops. In addition, GLP provides a platform for the land system science community through networking activities, such as the organization of workshops and conferences.

This paper aims to describe the development of land system science and its main achievements and provides a perspective of land system science within global environmental change research. Finally, the paper provides an outlook on emerging issues in land system science and identifies the challenges for the land system science community to translate explorative research into solution-oriented research, one of the priorities under the Future Earth initiative.

## 2. Land system science achievements

### 2.1. The development of land system science

Land system science has developed over the past twenty years. The study of land use and land cover change (coordinated through the LUCC project) was initially dominated by monitoring and modelling of the ecological impacts of major land cover changes on the natural system (Turner et al., 1993; Lambin et al., 2000; Lambin and Geist, 2006). An orientation towards sustainability always has been a constitutive element of land system science (Turner et al., 2007), and therefore key processes studied in case-study synthesis and land use modelling were deforestation and desertification. Achievements were made in terms of observing land cover changes by remote sensing for single case studies as well as in global datasets (Walsh and Crews-Meyer, 2002). As part of LUCC activities, Belward (1996) developed definitions of land cover

classes. The classification employed was developed to meet the needs of other IGBP projects. However, later it was recognised that specific projects and study objectives required different legends. The development of a common land cover legend became less of a priority for the LUCC community.

One of the main achievements of the early LUCC work was the synthesis of case studies to identify common driving factors of change and causation patterns (Geist and Lambin, 2002, 2004). At the same time, land use models were developed that allowed the exploration of future scenarios of land use change (Verburg et al., 1999; Pontius et al., 2001).

Besides the LUCC project the Global Change and Terrestrial Ecosystems (GCTE) project contributed by the research on terrestrial ecosystem changes under local, regional and global environmental changes such as increasing concentrations of greenhouse gases, changes in global and regional climate, habitat destruction, and increases in number and impacts of exotic invasive species (Pitelka et al., 2007). The overarching goal of the GCTE project was to project the effect of changes in climate, atmospheric composition, and land use on terrestrial ecosystem and to determine how these effects lead to feedbacks on the atmosphere and physical climate system. GCTE took the lead in analyzing the nature of nonlinear changes in Earth System functioning. This work played a central role in the emergence of abrupt change, surprises and extreme events as unifying themes in the second phase of IGBP research.

Gradually, the research field of land use and land cover change matured and became more integrative, focusing on both the drivers and impacts of land change and including a wider range of interacting processes of land use change. This development was stimulated by the strong exchanges with other communities working on related issues. The growing group of researchers engaged in this field led to the emergence of 'Land Change Science' as a separate, interdisciplinary, research field engaging scientists across the social, economic, geographical and natural sciences (Rindfuss et al., 2004; Turner et al., 2007). The increasing attention for the feedbacks between drivers and impacts (Verburg, 2006), the interactions between social and ecological systems and telecoupling between world regions (Lambin and Meyfroidt, 2011; Liu et al., 2013) and between cities and their rural hinterlands (Seto et al., 2012) have motivated an integrated socio-ecological systems perspective. In this integrated concept, land systems are conceptualised as the result of dynamic interactions within the socio-ecological system that operate across spatial and temporal scales. This perspective has also moved land system science from a focus on the most dramatic land cover changes to greater attention for subtle changes of human interactions with the natural surroundings, including land management (Erb et al., 2013; Kuemmerle et al., 2013) and the provisioning of a wide range of ecosystem services (Crossman et al., 2013). The following sections describe a number of major achievements of land system science over the past decade through illustrations of the different types of research conducted in this field.

### 2.2. Meta-analysis of land use drivers and impacts

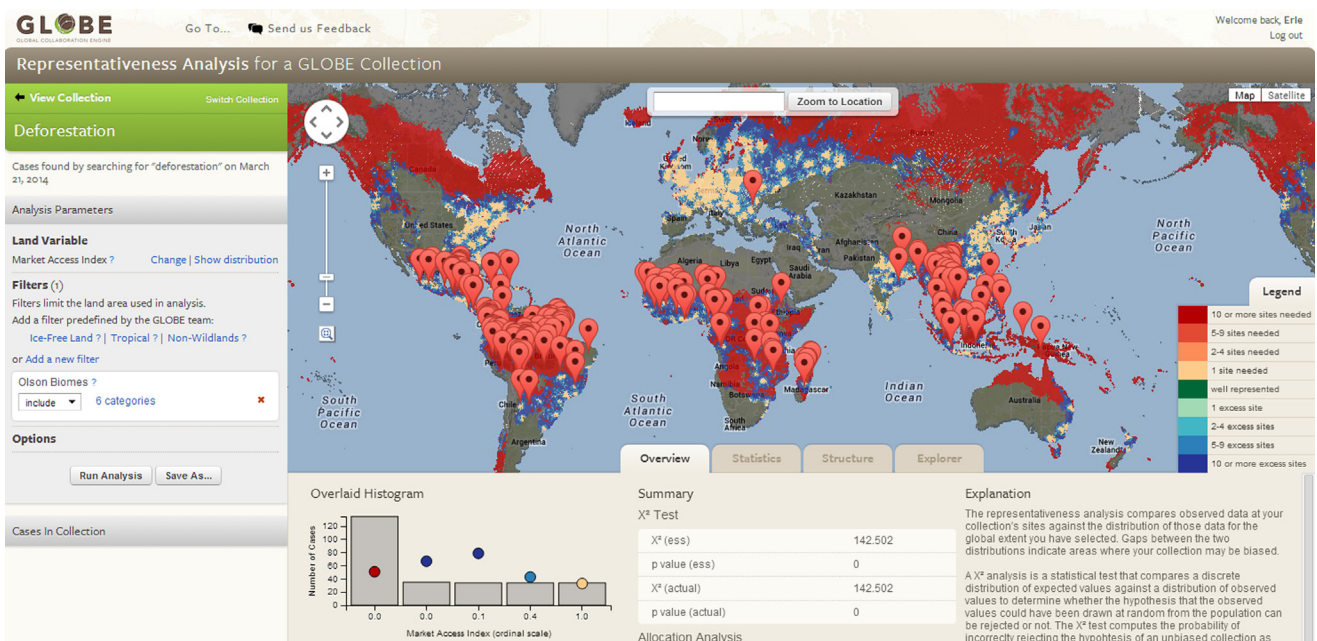
Place-based research in small case-studies has always formed a key component of land system science. In order to better contextualise individual case studies and identify generic patterns across case-studies, meta-analyses were conducted, focusing on the causes of key land change processes or consequences of land system change (Geist and Lambin, 2002, 2004; Keys and McConnell, 2005; Don et al., 2011; Gibson et al., 2011; Seto et al., 2011; van Vliet et al., 2012; Ziegler et al., 2012; Van Asselen et al., 2013). Methodological development of meta-analysis for the specific purpose of global environmental change and land system

science has also been carried out, e.g. on the utility of qualitative comparative analysis for comparing highly diverse case studies from different regions and the possibilities and caveats of using statistical analysis when case studies are not designed in a similar way (Rudel, 2008). Two recent studies provide an overview of synthesis and meta-analytical studies in land system science since 1995 (Magliocca et al., 2014; van Vliet et al., 2015). From the total of 181 studies analysed it became clear that while the number of meta-studies is increasing rapidly, more interaction between researchers focusing on meta-studies and those conducting case-study is needed to ensure that meta-analyses capture the essence of case-studies and that case-studies target the research gaps identified in meta-analysis. A tool developed in GLP context to further such integration is the GLOBE project. GLOBE (global collaboration engine; <http://globe.umbc.edu>) is an online collaborative environment designed for real-time assessment of the global context and relevance of local case studies, both individually and in collections, as used for meta-studies. To make this possible, GLOBE leverages an advanced geocomputation and visualization engine that couples local case-study locations with more than 100 global datasets characterizing social and environmental patterns across the Earth. Using GLOBE, site-based researchers quantify, map and publish the global relevance of their studies while identifying additional studies and researchers working in globally similar environments around the world. Researchers can engage in cross-site synthesis to assess geographic biases and global knowledge gaps across their case study collections (Fig. 1) and can correct them by adding more studies in underrepresented areas and by reweighting studies to better reflect their global abundance. With this type of tool, researchers can collaborate globally across sites, environments and social contexts with the ultimate aim of nurturing a robust culture of globally relevant knowledge creation and sharing in land system science.

### 2.3. Long-term histories of land use change

Land system science studies the past, current and projected state and dynamics of land use. Human use of land is a major

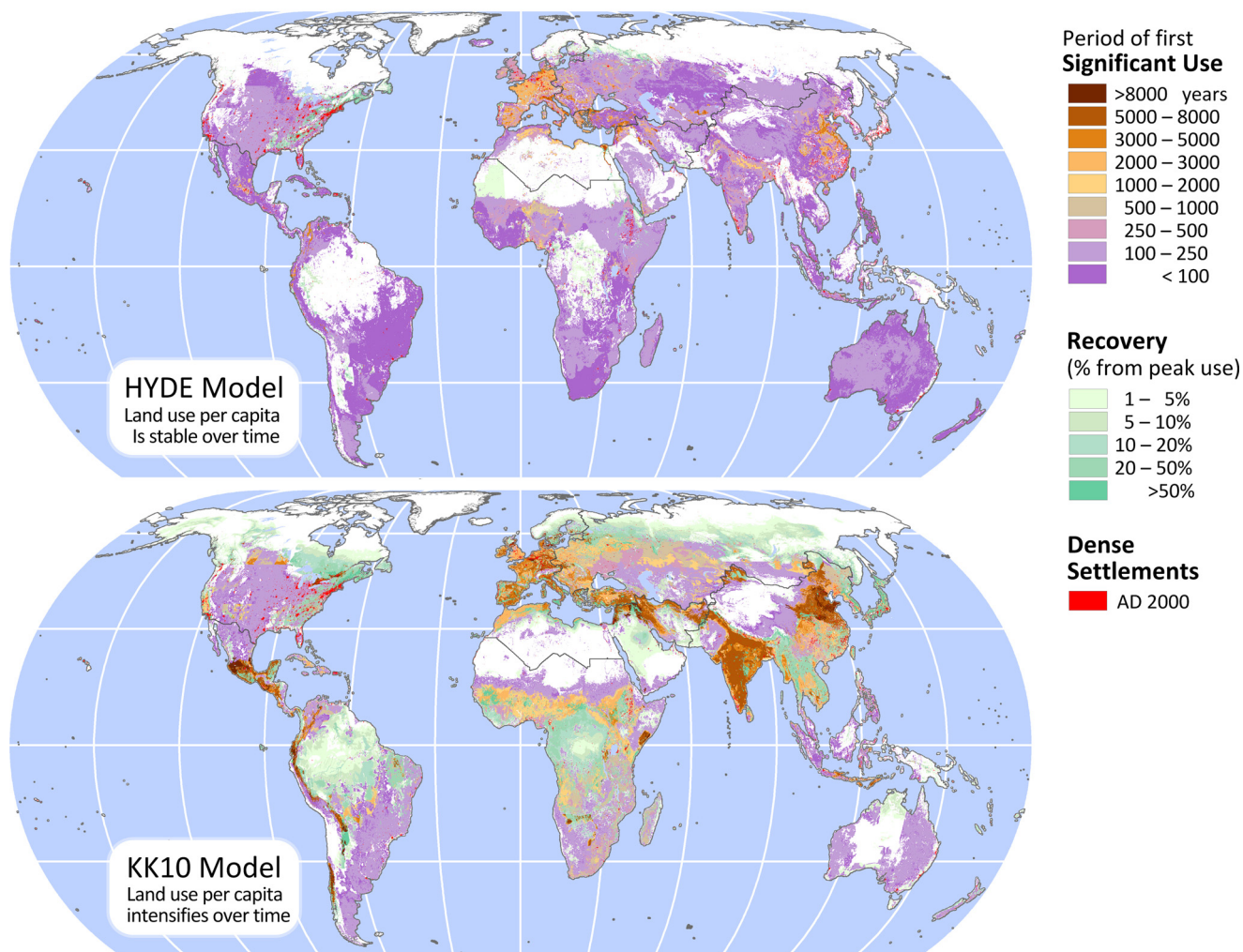
component of the long-term anthropogenic global changes in the Earth system that have underpinned the call for the Anthropocene as a new epoch of geologic time (Zalasiewicz et al., 2012). A collaborative effort was made to review and compare the latest global datasets on human populations and land use over the course of the past 8000 years to evaluate human use of land as a global force transforming the terrestrial biosphere (Ellis et al., 2013). Different historic reconstructions of global land use relying on different models of land use intensification produced radically different assessments of the emergence, history, and future of land use as a process transforming the Earth System (Fig. 2; (Klein Goldewijk et al., 2011; Kaplan et al., 2012; Ellis et al., 2013)). By combining these historical reconstructions with evidence on land use systems and their intensification from archaeology, paleoecology and environmental history, it was possible to explain why relatively small human populations could have caused widespread and profound ecological changes more than 3000 years ago, while in recent times the largest and wealthiest human populations in history are using less arable land per person every decade. While human population as well as biomass consumption by humans has grown fourfold and economic output 17-fold in the last decade, the global human appropriation of net primary production (HANPP) has only doubled in this period of time (Krausmann et al., 2013), mainly due to surges in food production per unit of land and the use of external (e.g., energy) inputs in agriculture. Reconstructions of past developments that take such adaptive changes in land-use systems over time into account, including land-use intensification, offered a more spatially detailed and plausible assessment of our planet's history, with a biosphere and perhaps even climate, long ago affected by humans (Fig. 2). Based on this assessment, further work to empirically validate a date for the emergence of land use as a global force transforming the biosphere and initiating the Anthropocene has been proposed (Ellis et al., 2013). While land-use processes are now diverging rapidly from historical patterns into new patterns and novel land systems, integrative global land-use models that incorporate dynamic adaptations in human-environment relationships help



**Fig. 1.** Global representativeness of 273 deforestation case studies identified by searching in GLOBE (of 875 total; published collection data (Ellis, 2014)). Colours indicate the coverage of case-studies across different classes of market access across Earth's woodlands, with red areas indicating significant gaps in study coverage in more remote regions.



## A Tale of Two Planets: Two different models of global land use history

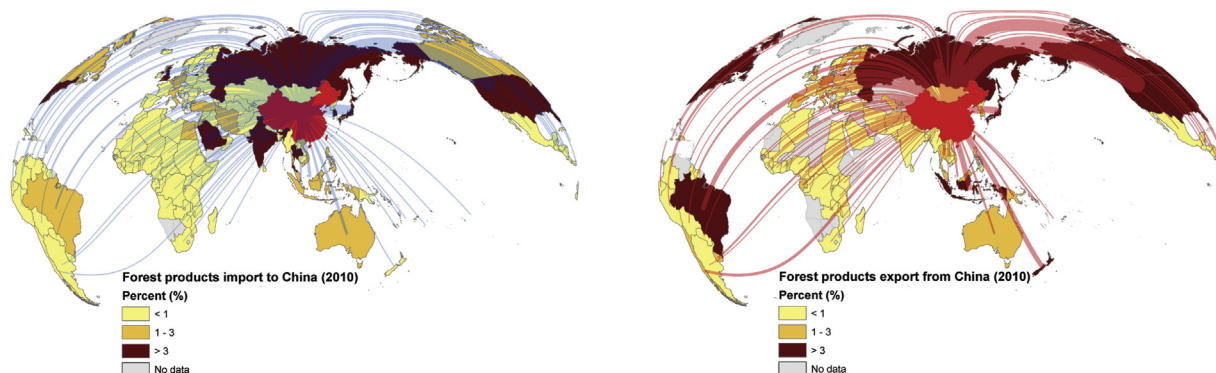


**Fig. 2.** Different land use intensification models produce different views of land use as a global force transforming the terrestrial biosphere. Maps show time period of first significant land use and recovery from peak land use, 6000 B.C.–A.D. 2000, based on two different historical land-use reconstructions (upper plate, HYDE, and lower plate, KK10 model that accounts for changes in land productivity per person). Reproduced with permission from Ellis et al. (2013).

to advance our understanding of both past and future land-use changes, including their sustainability and potential global effects.

### 2.4. Observing land change

Progress in land system science depends on both conceptual progress and availability of accurate land change data. Accelerating



**Fig. 3.** Map of imports and exports of forest products to and from China. (The countries are classified based on the percentage of imported or exported value.). (Source: Liu 2014, p. 7; reproduced with kind permission of the author).

global change and increasing global connections forces land system scientists to strive for more timely and accurate data. At the same time, our increasing knowledge of land change and the more sophisticated questions arising from that knowledge enforce the need for increased semantic depth in land use data. Data for land use change analyses are derived largely from remote sensing analyses or census information, or from finer scale field surveys, cadastres or participatory mapping. While much progress has been made in harmonizing such heterogeneous data, there are multiple challenges associated with spatially, temporally and thematically heterogeneous data sources and their inherent uncertainties (Verburg et al., 2011).

During the last decade two major developments have transformed land change data generation and analysis. Firstly, there has been a move from land cover to land use information as well as increased attention for the collection of qualitative information. This development is largely driven by the verdict that better information on land use intensification is needed to improve our understanding of global land changes which will in the future relate to land use intensification rather than land use conversions *sensu stricto* (Kuemmerle et al., 2013).

Secondly, higher resolution and more accurate global remote sensing based datasets have been developed since the early 2000s. While most of those global land observation products are based on data with a spatial resolution of hundreds of meters to one km (Achard et al., 2007; Fritz et al., 2013), new remote sensing capabilities can create higher resolution land change products at landscape scale (Hansen et al., 2013; Roy et al., 2014).

One prominent, but largely under-researched land change process is agricultural land abandonment. Studies relying on imagery-derived data help quantifying land abandonment and improving our understanding concerning this under-researched land change process (Kuemmerle et al., 2011; Griffiths et al., 2013). For example, remote sensing based analyses created much of our knowledge how the breakdown of the Soviet Union and collapsing markets triggered massive land abandonment in central and eastern Europe (Hostert et al., 2011; Prishchepov et al., 2012).

Another major challenge is differentiating similar land cover classes that have significantly different ecological properties. For example, in Latin America, natural grasslands (high diversity, high soil carbon, moderate/low primary productivity), are hardly discriminated from planted pastures (low biodiversity, moderate/low carbon, high primary productivity). Similarly, it is often also very difficult to discriminate between tree plantations and natural forests, and of course, between crops with very different ecological, economic and socioeconomic implications.

## 2.5. Modelling land system change

Land use modelling takes place using simulation tools covering a wide range of different model concepts originating from different disciplines. Models used in land system science range from global scale, coarse resolution models assessing global demand and supply of commodities produced by land systems (e.g. Computational General Equilibrium models), to local multi-agent models that simulate individual land use decisions at the level of individual actors. This wide range of models and modelling approaches can be explained by the different scales that land system science addresses, the different research and policy questions to which land use models are applied and the different disciplinary traditions from which land system science is originating. The range of different modelling approaches available is synthesised in various review papers (Verburg et al., 2004; Matthews et al., 2007; Priess and Schaldach, 2008; Brown et al., 2013). In a recent review for the National Research Council of the

United States models were classified according to the role they play within the process of supporting policy decisions (Brown et al., 2013; National Research Council, 2013). While some models are targeted as learning-tools to test alternative conceptualisations of land system dynamics, other models are specifically designed to evaluate alternative policy proposals to support decision making by assessing effectiveness and identifying potential trade-offs resulting from the direct and indirect impacts of the intended policies on land use. Other models are targeted at scenario analysis, either to inform large scale assessments of climate change or biodiversity impacts (Lotze-Campen et al., 2010; Pereira et al., 2010) or to detect specific land use trajectories foreseen under alternative scenarios (Verburg et al., 2010; Sleeter et al., 2012) in order to raise important policy issues and provide an early warning signal that policies can anticipate. While such use is increasing, land use models are not yet standard in major assessments such as those for IPCC and IPBES, even though land use change is a major driver of climate change, biodiversity and ecosystem services. Each model type and approach has its own specific niche of applications, and it is not possible to classify one approach as superior to other approaches. While pixel-based approaches using spatial data of site conditions as major determinants of the transition probability of land use are extremely popular due to their good fit with available data, many have made pleas for a wider adaptation of so called multi-agent models that can explicitly address variation in decision making and interactions amongst decision makers (Brown et al., 2013; Filatova et al., 2013; Rounsevell et al., 2014). Development of such models still faces some outstanding challenges, including modelling agents' behaviour, sensitivity analysis, verification, and validation; coupling socio-demographic, ecological, and biophysical models, and spatial representation. However, forward progress is being made on these challenges (Filatova et al., 2013). At the same time, in spite of the many developments of multi-agent models in land system science at the local scale it has proven difficult to operationalise and parameterise such models at regional and coarser scales, largely due to data limitations and lack of empirical knowledge of decision mechanisms (Smajgl et al., 2011).

Apart from using different land use model types for different applications and at different scales, the linking of models is becoming more popular. Especially given the requirement to establish an empirical grounding for land-change models, many scholars are moving towards the development of hybrid models that combine participatory, experimental, statistical, and simulation methods (National Research Council, 2013). To better represent cross-scale feedbacks and relationships, pixel-based models are used to downscale results of macro-economic models and nested approaches in which local dynamics feedback to higher-scale dynamics are being explored, making optimal use of the complementarities of different model types (Verburg et al., 2008; Rounsevell et al., 2012; Herrero et al., 2014). However, often model coupling is still following a top-down approach in which higher scale models constrain more detailed models that translate regional dynamics to land use change patterns. In such approaches feedbacks from adaptive behaviour and changes in decision making at the local scale to higher level system dynamics are ignored. Both empirical data and knowledge and modelling concepts are lacking to implement such feedbacks (Verburg et al., 2015).

While land use models have strongly evolved over the past decade, further development is needed to enhance their use in both academia and in interaction with stakeholders. Such development should focus on strengthening the spatio-temporal representation of land use decision making, cross-scale dynamics, and a stronger link to empirical data collection for parameterization and validation.

## 2.6. Telecoupling of land systems

Globalised markets, decisions by distant governments, and global agenda setting (e.g. in light of global change) influence local land use decisions to an ever increasing degree. Land system science has taken up the challenge to both enhance understanding of the interaction of coupled human–environmental system in a telecoupled world as well as provide new frameworks and concepts to inform evidence based decision and policy making.

For example, the recent reforestation in Vietnam is to a large degree based on displacement of logging through import of wood products from other countries (of which 50% was illegally logged) (Meyfroidt and Lambin, 2009). On a global level 52% of the reforestation (2003–2007) of seven countries that have recently undergone forest transition is based on such displacement effects (Meyfroidt et al., 2010). Economic globalisation therefore facilitates forest transition in one country through displacement effects and leads to an export of negative externalities (frequently to countries with weak land governance systems). In another example, forest exports and imports of China in 2010 illustrates the degree to which land is now a globalised good (Fig. 3). Between 1997 and 2010 China exported forest products to over 160 countries and imported forest products from over 170 countries (Liu, 2014). Such empirical evidence is crucial to enhance respective global policies, such as those related to global deforestation.

Recently, there have been different attempts to quantify these displacement effects of resource use, and land use specifically based on trade and consumption data (e.g. (Qiang et al., 2013; Weinzettel et al., 2013; Yu et al., 2013)). While the results are partly contradictory, they all show the high degree to which land and the resulting respective externalities have been globalised. These results motivate the clear need for further methodological advances in this field (Kastner et al., 2014) so that the land system science community can provide critical information and tools to support national, regional and global policy decision-making.

In addition to displacement effects, teleconnections of land systems involves other socioecological processes such as human and species migrations, large land acquisition by foreign owners (Messerli et al., 2014), or distant “transfers” of ecosystem services (e.g. through watershed conservation). Land system science has reacted to the conceptual challenge of these increased interactions of distant places and has already proposed different frameworks to address them (e.g. (Seto et al., 2012; Liu et al., 2013). Liu et al. (2013) discussed an integrated concept of telecoupling that encompasses both socioeconomic and environmental interactions among coupled human environmental system over wide distances. Their concept centres on differentiating between sending, receiving and spill over systems, the flow between these systems, and the agents, causes and effects within these systems. This move from place based to process based conceptualisation offers much potential to enhance the system understanding of a telecoupled world and contributes to more effective policies and action towards sustainable development. While the Liu et al. (2013) framework emphasises geographical distance, other works (Eakin et al., 2014) emphasised the importance of institutional distance, or governance disconnect, in telecoupling: distant systems can be strongly influencing nearby systems while institutions are local and unable to govern these flows. This view also emphasises the role of feedbacks arising from these mismatches to modify the governance systems.

## 3. Land system science as a crucial component of earth system science

Changes in the land system have many interactions with other components of the earth system. Aquatic and atmospheric systems

are influenced by the land system in manifold ways, e.g. through emissions of greenhouse gases, the water consumption of terrestrial vegetation and sediment run-off through rivers. Changes and configurations of land systems have a substantial impact on terrestrial biodiversity through changes in habitat conditions by fragmenting and modifying natural ecosystems. In all these interactions, the land system operates at the interface of human and biophysical systems, in which the environment is modified by humans responding to the opportunities offered by land resources and adapting to environmental change. In this section we outline a number of major interactions of land systems with other components of global environmental change that are often studied independently.

### 3.1. Land-atmosphere processes

Land-use and land-cover changes have contributed substantially to climate change and are expected to continue to do so in the future (Le Quéré et al., 2009; Pitman et al., 2009; Houghton et al., 2012) due to the release of large quantities of carbon when natural ecosystems (mostly forests) are converted into croplands or pastures, or due to changes in management or land-use intensity (Erb et al., 2013). Intensification of crop management leads to release of additional greenhouse gases, like N<sub>2</sub>O from fertiliser application (Zaehle et al., 2011), or CH<sub>4</sub> from cattle and rice production (Verburg and Denier van der Gon, 2001; Steinfeld et al., 2006). Changes that follow land use change in the surface reflectivity and the way absorbed energy is distributed towards evapotranspiration or heating at the near-surface affect regional climate substantially (Pitman et al., 2009; Pongratz et al., 2009). Changes in land systems can also result in increased carbon sequestration, due to e.g. the land-sparing effects of intensification, if not overcompensated by rebound effects (Lambin and Meyfroidt, 2011) or due to management changes in forests that do not result in changes in land cover, such as forest grazing or litter raking. Although much emphasis has been put on carbon fluxes related to land cover changes, the complex suite of biogeophysical effects of land use and cover change (Mahmood et al., 2014), as well as the equally important effects of changes in land management and intensity within land use classes (Luyssaert et al., 2014) are now increasingly recognised. To adequately describe the functioning of the Earth system, land use and management (change) need to be accounted for along other components including climate and natural ecosystems. Nevertheless, the recent 5th Assessment Report by the IPCC WG1 is the first where land use change has been explicitly, although rudimentarily, accounted for in projections of climate change. Recent, model-based studies, have shown that land use change has an important impact on the radiative forcing calculation (Jones et al., 2012) while, often ignored, spatio-temporal dynamics in land systems are not accounted for, thus underestimating the land system change impacts on climate change (Stocker et al., 2014; Fuchs et al., 2015; Fuchs et al., 2015). From a human system's perspective, climate and climate change also contribute to land use change (Mertz et al., 2010). Climate determines the types of crops that can be grown (Easterling et al., 2007; Gornall et al., 2010). Harvest failures following floods, heat-waves or droughts can lead to food-shortages, and increases in local and global grain prices (Beddington, 2010). Indirect climate-effects like fires or insect-outbreaks can also affect the yield of forests and crops. At the same time, in other regions climate change also favours higher agriculture yields in areas currently limited by temperature and rainfall. As an example, the agriculture production of Argentina (one of the major global food producers) has been favoured by climate change (via rainfall increase) in recent decades. While such feedbacks through biophysical processes have been captured in integrated assessment models,



the human feedbacks through adaptive behaviour and decision making have been largely ignored and require both empirical research and representation in models (Rounsevell et al., 2014).

An emerging challenge is, therefore, to quantify impacts and feedbacks among land systems, the societies managing these systems, and the climate system, and to take into consideration regional to global scales and short- and longer-term time perspectives. A global scale perspective is needed because climate systems operate on global scales, and land systems are increasingly influenced by drivers at these scales, as illustrated in section 2.6. The debate on indirect land use change arising from land-based bioenergy production is a prominent example of global-scale dynamics (Fargione et al., 2008), but equally important is the possibility to supply food to regions that suffer from, for example, a climate-induced crisis. Issues of time arise from legacy effects of land use change in the climate system (Houghton et al., 2012) or from time-lags between introduction of a climate policy and its actual take-up by local farmers (Alexander et al., 2013). The climate, environmental and socio-economic research communities are confronted with providing the required understanding of the fundamental processes that operate at the interface of the climate and land systems, and their manifold interactions across local, regional, and global scales. A key challenge is to find ways to bridge, philosophically and methodologically, the diverse scientific communities. Finding ways to synthesise available data and knowledge in these communities will allow further development of the mechanisms represented in models, advance our capacity to evaluate model performance, and yield information to support policy development and societies towards successful adaptation and mitigation strategies (Hibbard et al., 2010; Rounsevell et al., 2014).

### 3.2. Urban rural teleconnections

Over half of the world's population already lives in cities, with a massive increase in urban population projected by 2050, with an anticipated increase in urban land cover about twice the increase in urban population (Seto et al., 2011). Rates of urbanization are spatially uneven, with Asia and Africa projected to account for as much as 86% of projected urban growth (United Nations, 2010). Alongside rapid growth, urban shrinkage is also taking place in many parts of Europe and North America (Haase et al., 2012). Conversion of land to built-up is often considered one of the most problematic trajectories of land change, due to its perceived irreversibility and severe consequences for climate, biodiversity, ecosystem quality and ecosystem services, which are difficult to mitigate and manage (Elmqvist et al., 2013). Urban green spaces, wetlands and water bodies provide critical biodiversity and ecosystem services for all city dweller, and are especially important for poor and vulnerable populations, such as urban slum residents (Nagendra et al., 2013c). Thus, protecting and restoring urban ecosystems is an important issue for sustainable urbanization.

Economic and demographic factors appear to be particularly strong drivers of urban land change in China, India and Africa (Seto et al., 2011). Macroeconomic factors have increased in their influence, while the drivers are often spatially removed from the locations of change, and stakeholders increasingly globalised African urbanization further constitutes a particular information gap, with studies of land change in African cities being relatively sparse compared to other parts of the world, as a recent meta-analysis indicates (Seto et al., 2011). Peri-urban regions constitute areas of particularly rapid change that are especially vulnerable to land acquisitions and tenure changes with potentially disrupting socioeconomic effects and ecosystem degradation (Seto et al., 2012), further increasing the social vulnerability of the urban

poor, migrants and people practising traditional rural livelihoods. In order to understand, model and manage the multi-level drivers of urbanization in cities and their peri-urban surroundings, recent efforts are beginning to focus on developing a better understanding of urban-rural teleconnections (Seto et al., 2012). As an example, Aide and Grau (2004) show that by reducing rural population pressure in areas marginal for agriculture production, rural to urban migration may facilitate the recovery of natural ecosystems while at the same time, the quality of life for the rural-to-urban migrants improves. Land system scientists suggest a more nuanced, continuous representation of urbanity and rurality across multiple dimensions of livelihood, lifestyle and teleconnectivity, as an advance beyond traditional conceptualizations of an rural-urban gradient or divide (Nagendra et al., 2013b; Boone et al., 2014). Achieving sustainable land uses in an urban era requires moving beyond the vision of cities as centres of consumption that externalise land use impacts on rural hinterlands, and acknowledging that cities and urban lifestyles and institutions can also contribute to solutions (Seto and Reenberg, 2014).

### 3.3. Land governance

Land systems are increasingly affected by changes in global governance and wider revalorizations of land, and in turn influence the wider transformations in governance and value (see Fig. 4). For example, global demand for food and biofuels drives one of the most visible revalorizations of land over the past decade, giving rise to large-scale land acquisitions by states, transnational corporations and financial investors (Anseeuw et al., 2012; White et al., 2012). The land acquisitions have been enabled by larger governance changes at the international, national and local levels, such as the ascendancy of the World Trade Organization, national policies on food, agriculture and trade, and the rolling out of commercial land markets (Peluso and Lund, 2011; McMichael, 2012; Margulis et al., 2013). Simultaneously, indigenous peoples have mobilised in the pursuit of political and cultural goals, highlighting the value of land as a place of belonging, territory for self-determination and religious practice (Sikor and Stahl, 2011). Changes in land systems drive global revalorizations of land and wider transformations of governance, including multilateral agreements, as illustrated by the inclusion of forests in global climate mitigation efforts due to concerns over land-related carbon emissions. Thousands of small-scale reforestation projects in the so-called voluntary sector and the United Nations initiative of Reducing Emissions from Deforestation and Forest Degradation (REDD+) have brought increasing attention to carbon storage and changes in land governance that accommodate the challenge of climate change (Bumpus and Liverman, 2008; Corbera and Schroeder, 2011), but land systems science has also highlighted the complexities of governing climate change with often unpredictable and complex changes that occur in land systems (Ankersen et al., 2015).

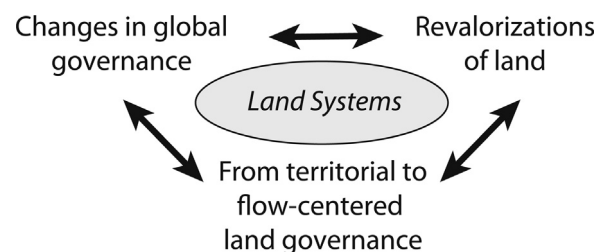


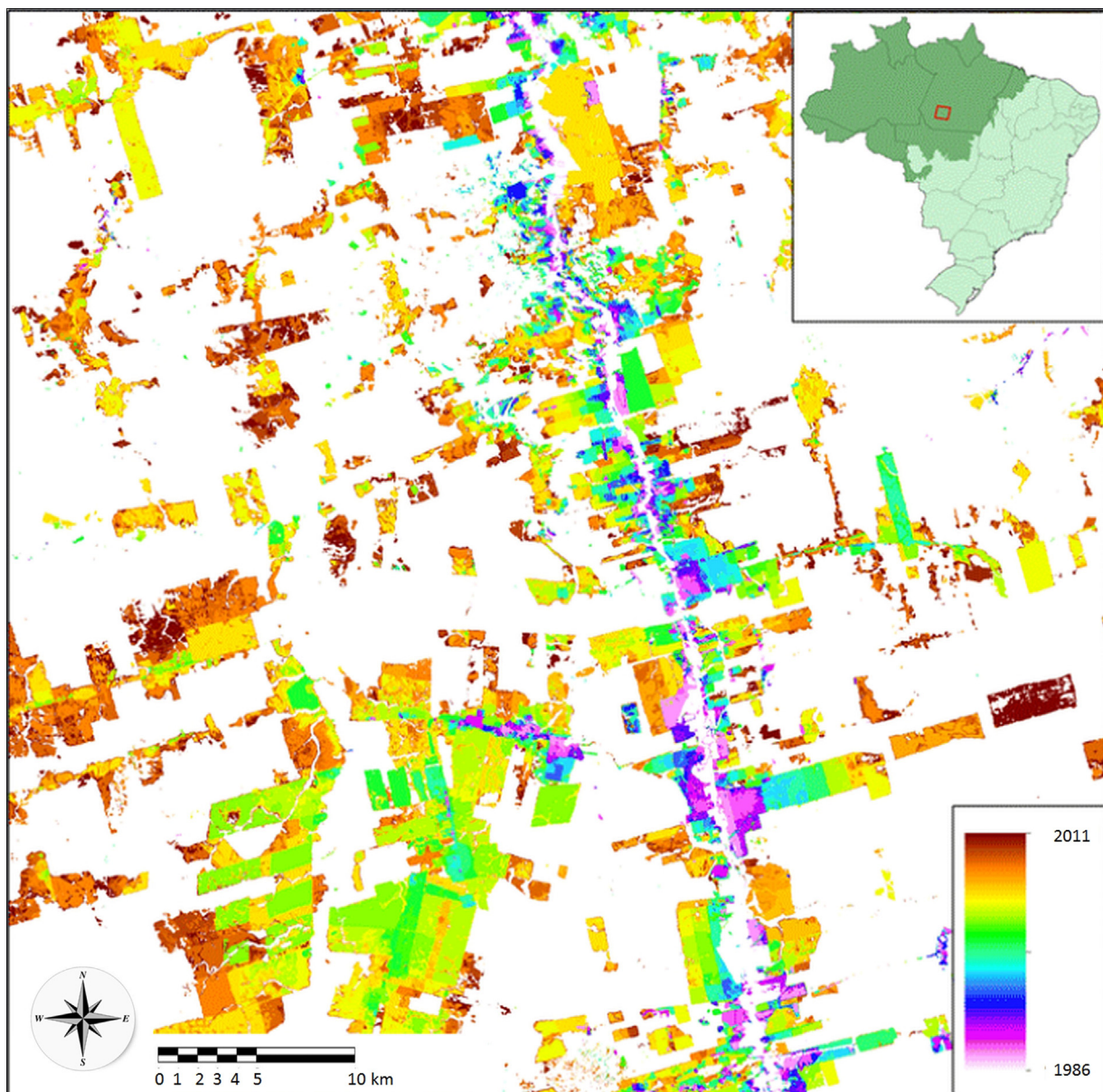
Fig. 4. Dynamics of land governance and value.



In reaction to shifts in governance, value and land systems, land governance is partly shifting from 'territorial' toward 'flow-centered' arrangements (Sikor et al., 2013). Flow-centered governance targets particular flows of resources or goods, such as certification of agricultural or wood products or voluntary regulation in the mining sector (Auld, 2014). For example, concentration in global agri-food supply chains has enabled industry to introduce production and sustainability standards (Bailis and Baka, 2011). Initially NGOs, but later also governments have promoted certification schemes for food at global or regional levels (Auld, 2010). The European Union and USA are now seeking to regulate global timber production through trade-related measures. These forms of flow-centered governance complement classic territorial forms of land governance, such as the designation of protected areas, regulation of land use, and land use planning (Sikor and Müller, 2009). They also add to the new instruments used in territorial governance, in particular financial mechanisms such as Payments for Ecosystem Services (Muradian et al., 2010).

### 3.4. Land change and ecosystem services/biodiversity

Ecosystem services are supplied directly by natural capital, i.e. the major components of the land system: soil, water, vegetation and biota. Land use and land use change decisions therefore have direct bearing on natural capital and ecosystem service supply (Foley et al., 2005). The impacts of these decisions typically unfold at local to regional scales, affecting local livelihoods that depend on ecosystem services and biodiversity (Wu, 2013b). Trade-offs often arise between bundles of ecosystem services supplied by alternative land uses (Chisholm, 2010; Crossman et al., 2011; Smith et al., 2013). For example, land use change from natural forest to annual cropping or grazing systems (Fig. 5) may enhance supply of the food production ecosystem service, but at the cost of a number of other services, such as water purification, local climate regulation, carbon sequestration, biodiversity and habitat, and important cultural and spiritual values (Smith et al., 2013). Robust quantification of the many services supplied by natural capital



**Fig. 5.** Yearly map of primary forests converted to rangelands in the Brazilian Amazon along the BR 163 highway. Improved food production services on the expense of carbon sequestration, biodiversity and habitat.

is critical for understanding the trade-offs between services under alternative land use scenarios. Land system science plays a pivotal role in quantifying the bio-physical processes underpinning ecosystem services. In some instances the processes are well understood (e.g. sediment transport processes under alternative land use arrangements), whereas in other cases the processes have yet to be fully described (e.g. the distribution of biodiversity and supply of habitat-related ecosystem services (Nagendra et al., 2013a)).

There is an important social dimension to natural capital and ecosystem services that land change science can help better elucidate. Arguably, ecosystem services are co-produced by human-environment interactions, and do not exist if there are no beneficiaries (Wolff et al., 2015). There is a clear need to better understand the spatial and temporal dimensions of beneficiaries, and whether they are spatially and temporally connected or disconnected from where ecosystem services are supplied (Serna-Chavez et al., 2014). Furthermore, land system science also aims to understand the impact of human decisions on natural capital and ecosystem service supply. Yet this is an area of greatest uncertainty necessitating deeper collaborations between land system science and the social sciences (Crossman et al., 2013).

#### 4. Land system science: from understanding to sustainability solutions

##### 4.1. Land system science contributions to sustainability solutions

In 2013, a new initiative gathering all previous global environmental change programmes was established and named 'Future Earth', in response to a visioning process on Earth System Science and Global Sustainability undertaken by ICSU (Reid et al., 2010). This Global Land Project transitioned to Future Earth in 2014. Future Earth prioritises a stronger focus on interdisciplinarity and science that supports sustainability transitions through co-design and co-production of research together with stakeholders. While interdisciplinarity is central to land system science, land system science could benefit from a stronger engagement of stakeholders to develop sustainability solutions. Although the orientation towards sustainability has a long tradition in land system science, a lot of research is focused on understanding the drivers and impacts of land system changes (see Section 2.1), where large knowledge gaps still remain. However, there is also a need to further engage in using the acquired knowledge to develop and prototype sustainable land management practices and policies. Land system science is closely related to the fields of land use planning and land use policy. However, with much land being owned and managed by private land owners that are, for various reasons, not always directly responding to planning and policy, new ways of linking science and practice need to be developed to effectively create scientific findings that contribute to sustainability solutions.

Important ways forward in this perspective include the evaluation and design of alternative ways to govern land resources (Deininger et al., 2011; Bourgoïn et al., 2012; Sikor et al., 2013). Studies in Laos exemplify how trans-disciplinary research can contribute to this. In Laos there is an immense commercial pressure on land and authorities and private operators seek to replace the traditional shifting cultivation practices with more commercially oriented agriculture. Development-oriented research endeavors have been co-designed with local and governmental stakeholders leading to more effective approaches to local land use planning (Bourgoïn et al., 2012). These approaches capture and contextualise for the first time the immense magnitude of land investment in the country (Schönweger et al., 2012) as well as traditional smallholder claims on land through

shifting cultivation (van Vliet et al., 2012; Heinimann et al., 2013). This co-production of knowledge led to the recognition by officials of the need for more efficient and participatory strategies for land management and improved access to land for smallholder communities. It also contributed to the declaration of a land concession moratorium (for rubber, eucalyptus and mining) by the prime minister office of Laos, and to increased recognition of the importance of shifting cultivation in the new Upland Strategy of the government. Whether this is then translated into locally appropriate development has yet to be seen and land system science has an important role to document such policy changes with case studies at local level in Laos and elsewhere.

Land system science can also make major contributions to the search for solutions to meet the multiple, conflicting, demands on the land system. In particular the challenge to produce more food for a growing and more demanding population while avoiding the detriments of many output-enhancing land-use practices, such as biodiversity loss and the degradation of ecosystem service provision, has given rise to debate about alternative strategies of land management (Rosegrant and Cline, 2003; Godfray et al., 2010; Ingram, 2011; Lambin and Meyfroidt, 2011). This debate has been influenced by strong opinions in favour of either intensification of agricultural production on a relatively limited area, so-called land sparing, or multi-functional agriculture areas, referred to as land sharing (Phalan et al., 2011; Butsic et al., 2012; Tschamtké et al., 2012). Whereas intensive agriculture has been characterised by negative environmental and social externalities, multi-functional agriculture has often been characterised by lower yields, thus requiring larger areas to produce the same quantities of agricultural product. However, in reality these tradeoffs are very dependent on the biophysical and socio-economic context. In sensitive environments, organic or other extensive, multifunctional, forms of agriculture can be suitable options. At the same time, intensive agriculture can, with appropriate technologies and management, produce large quantities of commodities fulfilling the food demand of many people on a relatively small land area. Matching land use systems with the abilities and willingness of the land managers, the local environmental conditions and the demand for ecosystem services is important to achieve sustainable land management. In a globalised world locally optimal solutions need to be contextualised as choices that always have wider implications: the choice for relatively unproductive systems has trade-offs due to displacement of production to other places (Lambin and Meyfroidt, 2011). It is incorrect to assume that intensification will always spare land that can be used for conservation purposes. Increased production can trigger increased consumption as a result of lower prices and improved agricultural opportunities may attract new activities on 'spared' land (Matson and Vitousek, 2006; Lambin and Meyfroidt, 2011; Phalan et al., 2011; Grau et al., 2013; Hertel et al., 2014). Land system science can provide insights in both the local and global tradeoffs. The quantification of the global scale tradeoffs of locally sustainable solutions can inform land management and conservation decisions, and bring nuance into discussions about land sparing and sharing paradigms by accounting for local context and environmental heterogeneity (Bryan and Crossman, 2013).

The conceptual and methodological studies to evaluate trade-offs can support a land system architecture, which draws on principles of landscape ecology about spatial structure and pattern (Wu, 2013a), to design novel land systems that more optimally account for spatial and temporal interactions and landscape configuration (Bateman et al., 2013; Crossman et al., 2013; Seppelt et al., 2013; Turner et al., 2013). By modifying spatial landscape structure and allocating land use activities to the most optimal places in the landscape, it is possible to enhance the production of multiple services and the resilience of the land system

(Bryan et al., 2011). Such a design-based approach needs a comprehensive knowledge base, thus requiring engaging with stakeholders through co-design and transdisciplinary approaches. In this way the designed systems may better fit the local interests and ecosystem service demand, be sustainable from both local and global perspectives and fit to the local socio-economic and land governance systems (Bryan et al., 2010). Such research requires the use of participatory techniques but also the involvement of practitioners to prototype the newly designed land systems and test their suitability in reality. The approach aims to use the capacity of land systems and the architecture of these systems to simultaneously respond to changing societal demand and support mitigation and adaption to environmental change. That way, land system science would not only play a role at the interface of the social and natural sciences, but also at the interface between science and practice.

#### 4.2. Land system science as a platform for interdisciplinary and transdisciplinary collaboration in global change research

The position of land system science at the interface of human and environmental systems makes it central to studies across different scales and disciplinary perspectives, thus creating a platform to bring the different communities and disciplines together, exchange and compare approaches, and create a mutual understanding of the challenges and knowledge gaps. International global change programmes projects LUCC, GCTE and GLP have been successful in creating such platforms. In addition to creating an awareness of different perspectives and methods, the interactions in these projects have facilitated, at various stages, knowledge synthesis and evolution of research agendas and priorities. The knowledge gaps related to global environmental change cannot be addressed by a single core project or within one research community, re-iterating the grand challenge for more interdisciplinarity in global change research identified during the process towards the establishment of Future Earth (Reid et al., 2010). Land systems at the interface of human and environmental systems provide a unique platform for interaction amongst the different global change communities.

## 5. Conclusions

Land use has been a central element for society throughout human history and remains even more so today. However, land systems, their characteristics, dynamics, constraints and impacts, have traditionally been studied as part of different disciplines, including economics, ecology and geography. The increasing pressures on land resources and the key role of land systems within the Earth system dynamics have given rise to the development of land system science as an interdisciplinary field that acts as a platform to integrate different perspectives and dimensions of global change research. The field has matured during recent decades giving rise to novel approaches to bridge the different scales of analysis as well as facilitating the establishment of links between science and practice.

Land systems are both a cause of global environmental change and a possible powerful means of mitigation of and adaptation to global environmental change. In order to exploit this potential, the community needs to move from a dominant focus on exploratory research towards understanding the functioning of the land system and its dynamics to approaches that use this knowledge together with stakeholders to mitigate and adapt to the changing environmental and socio-economic context. The concept of land governance opens up many points of connection with stakeholders, including both formal organizations various local, national and global fora where people make collective decisions about land.

The competition for land resources and the services provided by the land are increasingly dynamic in response to the high demands of a growing population under a changing climate. In this paper we have identified priority areas that require more attention during the coming years to be able to effectively address these challenges. The knowledge and commitment embedded in land system science can contribute to co-designing land system solutions to these global change challenges.

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## References

- Achard, F., DeFries, R., Eva, H., Hansen, M., Mayaux, P., Stibig, H.J., 2007. Pan-tropical monitoring of deforestation. *Environ. Res. Lett.* 2, 045022.
- Aide, T.M., Grau, H.R., 2004. Globalization, migration, and Latin American ecosystems. *Science* 305, 1915–1916.
- Alexander, P., Moran, D., Rounsevell, M.D.A., Smith, P., 2013. Modelling the perennial energy crop market: the role of spatial diffusion. *J. R. Soc. Interface* 10, 20130656.
- Ankersen, J., Grogan, K., Mertz, O., Fensholt, R., Castella, J.-C., Lestrelin, G., Nguyen, D., Danielsen, F., Brofeldt, S., Rasmussen, K., 2015. Vietnam's forest transition in retrospect: demonstrating weaknesses in business-as-usual scenarios for REDD+. *Environ. Manage.* 55, 1080–1092.
- Anseu, W., Boche, M., Breu, T., Giger, M., Lay, J., Messerli, P., Nolte, K., 2012. Transnational Land Deals for Agriculture in the Global South. Analytical Report based on the Land Matrix Database. CDE/CIRAD/GIGA, Bern, Montpellier, Hamburg.
- Auld, G., 2010. Assessing certification as governance: effects and broader consequences for coffee. *J. Environ. Dev.* 19, 215–241.
- Auld, G., 2014. Private market-based regulation: What they are, and what they mean for land-use governance. In: Seto, K.C., Reenberg, A. (Eds.), *Rethinking Global Land Use in an Urban Era*. MIT Press.
- Bailis, R., Baka, J., 2011. Constructing sustainable biofuels: governance of the emerging biofuel economy. *Ann. Assoc. Am. Geogr.* 101, 827–838.
- Bateman, I.J., Harwood, A.R., Mace, G.M., Watson, R.T., Abson, D.J., Andrews, B., Binner, A., Crowe, A., Day, B.H., Dugdale, S., Fezzi, C., Foden, J., Hadley, D., Haines-Young, R., Hulme, M., Kontoleon, A., Lovett, A.A., Munday, P., Pascual, U., Paterson, J., Perino, G., Sen, A., Siriwardena, G., van Soest, D., Termansen, M., 2013. Bringing ecosystem services into economic decision-making: land use in the United Kingdom. *Science* 341, 45–50.
- Beddington, J., 2010. Global food and farming futures. *Philos. Trans. R. Soc. B* 365, 2767.
- Belward, A.S., 1996. The IGBP-DIS Global 1 km Land Cover Data Set DISCover: Proposal and Implementation Plans: Report of the Land Recover Working Group of IGBP-DIS. IGBP-DIS.
- Boone, C.G., Redman, C.L., Blanco, H., Haase, D., Koch, J., Lwasa, S., Nagendra, H., Pauleit, S., Pickett, S.T.A., Seto, K.C., Yokohari, M., 2014. Reconceptualizing land for sustainable urbanity. In: Seto, K.C., Reenberg, A. (Eds.), *Rethinking Global Land Use in an Urban Era*. MIT Press, Cambridge, MA.
- Bourgoin, J., Castella, J.-C., Pullar, D., Lestrelin, G., Bouahom, B., 2012. Toward a land zoning negotiation support platform: Tips and tricks for participatory land use planning in Laos. *Landscape Urban Plan.* 104, 270–278.
- Brown, D.G., Verburg, P.H., Pontius Jr., R.G., Lange, M.D., 2013. Opportunities to improve impact, integration, and evaluation of land change models. *Curr. Opin. Environ. Sustain.* 5, 452–457.
- Bryan, B.A., Crossman, N.D., 2013. Impact of multiple interacting financial incentives on land use change and the supply of ecosystem services. *Ecosyst. Serv.* 4, 60–72.
- Bryan, B.A., Crossman, N.D., King, D., Meyer, W.S., 2011. Landscape futures analysis: assessing the impacts of environmental targets under alternative spatial policy options and future scenarios. *Environ. Model. Software* 26, 83–91.
- Bryan, B.A., Raymond, C.M., Crossman, N.D., Macdonald, D.H., 2010. Targeting the management of ecosystem services based on social values: where, what, and how? *Landscape Urban Plan.* 97, 111–122.
- Bumpus, A.G., Liverman, D.M., 2008. Accumulation by decarbonization and the governance of carbon offsets. *Econ. Geogr.* 84, 127–155.
- Butsic, V., Radeloff, V.C., Kuemmerle, T., Pidgeon, A.M., 2012. Analytical solutions to trade-offs between size of protected areas and land-use intensity. *Conserv. Biol.* 26, 883–893.



- Chisholm, R.A., 2010. Trade-offs between ecosystem services: Water and carbon in a biodiversity hotspot. *Ecol. Econ.* 69, 1973–1987.
- Corbera, E., Schroeder, H., 2011. Governing and implementing REDD+. *Environ. Sci. Policy* 14, 89–99.
- Crossman, N.D., Bryan, B.A., de Groot, R.S., Lin, Y.-P., Minang, P.A., 2013. Land science contributions to ecosystem services. *Curr. Opin. Environ. Sustain.* 5, 509–514.
- Crossman, N.D., Bryan, B.A., Summers, D.M., 2011. Carbon payments and low-cost conservation. *Conserv. Biol.* 25, 835–845.
- Deininger, K., Selod, H., Burns, T., 2011. The Land Governance Assessment Framework: Identifying and Monitoring Good Practice in the Land Sector. World Bank, Washington.
- Don, A., Schumacher, J., Freibauer, A., 2011. Impact of tropical land-use change on soil organic carbon stocks—a meta-analysis. *Global Change Biol.* 17, 1658–1670.
- Eakin, H., Defries, R., Kerr, S., Lambin, E.F., Liu, J., Marcotullio, P.J., Messerli, P., Reenberg, A., Rueda, X., Swaffield, S.R., 2014. Significance of telecoupling for exploration of land-use change. In: Seto, K.C., Reenberg, A. (Eds.), *Rethinking Global Land Use in an Urban Era*. MIT Press, Cambridge, MA.
- Easterling, W.E., Aggarwal, P.K., Batima, P., Brander, K.M., Erda, L., Howden, S.M., Kirilenko, A., Morton, J., Soussana, J.-F., Schmidhuber, J., Tubiello, F.N., 2007. Food, fibre and forest products. *Climate Change 2007: impacts, adaptation and vulnerability*. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Cambridge University Press, Cambridge, UK, pp. 273–313.
- Ellis, E., 2014. Deforestation. *GLOBE Collection of Georeferenced Case Studies*. <http://dx.doi.org/10.7933/K100001H>.
- Ellis, E.C., Kaplan, J.O., Fuller, D.Q., Vavrus, S., Klein Goldewijk, K., Verburg, P.H., 2013. Used planet: a global history. *Proc. Natl. Acad. Sci. U. S. A.* 110, 7978–7985.
- Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P., McDonald, R., Parnell, S., Schewenius, M., Sendstad, M., Seto, K., Wilkinson, C., Alberti, M., Folke, C., Frantzeskaki, N., Haase, D., Katti, M., Nagendra, H., Niemelä, J., Pickett, S.A., Redman, C., Tidball, K., 2013. Stewardship of the biosphere in the urban era. In: Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J., McDonald, R.L., Parnell, S., Schewenius, M., Sendstad, M., Seto, K.C., Wilkinson, C. (Eds.), *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities*. Springer, Netherlands, pp. 719–746.
- Erb, K.-H., Haberl, H., Jepsen, M.R., Kuemmerle, T., Lindner, M., Müller, D., Verburg, P.H., Reenberg, A., 2013. A conceptual framework for analysing and measuring land-use intensity. *Curr. Opin. Environ. Sustain.* 5, 464–470.
- Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land clearing and the biofuel carbon debt. *Science* 319, 1235–1238.
- Filatova, T., Verburg, P.H., Parker, D.C., Stannard, C.A., 2013. Spatial agent-based models for socio-ecological systems: Challenges and prospects. *Environ. Model. Software* 45, 1–7.
- Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global Consequences of land use. *Science* 309, 570–574.
- Fritz, S., See, L., You, L., Justice, C., Becker-Reshef, I., Bydekerke, L., Cumani, R., Defourny, P., Erb, K., Foley, J., Gilliams, S., Gong, P., Hansen, M., Hertel, T., Herold, M., Herrero, M., Kayitakire, F., Latham, J., Leo, O., McCallum, I., Obersteiner, M., Ramankutty, N., Rocha, J., Tang, H., Thornton, P., Vancutsem, C., van der Velde, M., Wood, S., Woodcock, C., 2013. The need for improved maps of global cropland. *Eos, Transactions American Geophysical Union* 94, 31–32.
- Fuchs, R., Herold, M., Verburg, P.H., Clevers, J.G.P.W., Eberle, J., 2015. Gross changes in reconstructions of historic land cover/use for Europe between 1900 and 2010. *Global Change Biol.* 21, 299–313.
- Geist, H.J., Lambin, E.F., 2002. Proximate causes and underlying driving forces of tropical deforestation. *Bioscience* 52, 143–150.
- Geist, H.J., Lambin, E.F., 2004. Dynamic causal patterns of desertification. *Bioscience* 54, 817–829.
- Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E., Sodhi, N.S., 2011. Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature* 478, 378–381.
- GLP, 2005. Science Plan and Implementation Strategy Global Land Project. IGBP Report No. 53/IHDP Report No. 19. IGBP Secretariat, Stockholm.
- Godfray, H.C., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 Billion people. *Science* 327, 812–818.
- Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K., Wiltshire, A., 2010. Implications of climate change for agricultural productivity in the early twenty-first century. *Philos. Trans. R. Soc. B* 365, 2973–2989. doi:<http://dx.doi.org/10.1098/rstb.2010.0158>.
- Grau, R., Kuemmerle, T., Macchi, L., 2013. Beyond 'land sparing versus land sharing': environmental heterogeneity, globalization and the balance between agricultural production and nature conservation. *Curr. Opin. Environ. Sustain.* 5, 477–483.
- Griffiths, P., Müller, D., Kuemmerle, T., Hostert, P., 2013. Agricultural land change in the Carpathian ecoregion after the breakdown of socialism and expansion of the European Union. *Environ. Res. Lett.* 8, 045024.
- Haase, D., Haase, A., Kabisch, N., Kabisch, S., Rink, D., 2012. Actors and factors in land-use simulation: the challenge of urban shrinkage. *Environ. Model. Software* 35, 92–103.
- Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st-century forest cover change. *Science* 342, 850–853.
- Heinimann, A., Hett, C., Hurni, K., Messerli, P., Epprecht, M., Jørgensen, L., Brey, T., 2013. Socio-economic perspectives on shifting cultivation landscapes in Northern Laos. *Hum. Ecol.* 41, 51–62.
- Herrero, M., Thornton, P.K., Bernués, A., Baltenweck, I., Vervoort, J., van de Steeg, J., Makokha, S., van Wijk, M.T., Karanja, S., Rufino, M.C., Staal, S.J., 2014. Exploring future changes in smallholder farming systems by linking socio-economic scenarios with regional and household models. *Global Environ. Change* 24, 165–182.
- Hertel, T.W., Ramankutty, N., Baldos, U.L.C., 2014. Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO<sub>2</sub> emissions. *Proc. Natl. Acad. Sci. U. S. A.* 111, 13799–13804.
- Hibbard, K., Janetos, A., van Vuuren, D.P., Pongratz, J., Rose, S.K., Betts, R., Herold, M., Feddema, J.J., 2010. Research priorities in land use and land-cover change for the Earth system and integrated assessment modelling. *Int. J. Climatol.* 30, 2118–2128.
- Hostert, P., Kuemmerle, T., Prishchepov, A., Sieber, A., Lambin, E.F., Radeloff, V.C., 2011. Rapid land use change after socio-economic disturbances: the collapse of the Soviet Union versus Chernobyl. *Environ. Res. Lett.* 6, 045201.
- Houghton, R.A., House, J.I., Pongratz, J., van der Werf, G.R., DeFries, R.S., Hansen, M.C., Le Quéré, C., Ramankutty, N., 2012. Carbon emissions from land use and land-cover change. *Biogeosciences* 9, 5125–5142.
- Ingram, J., 2011. A food systems approach to researching food security and its interactions with global environmental change. *Food Secur.* 3, 417–431.
- Jones, A.D., Collins, W.D., Edmonds, J., Torn, M.S., Janetos, A., Calvin, K.V., Thomson, A., Chini, L.P., Mao, J., Shi, X., Thornton, P., Hurtt, G.C., Wise, M., 2012. Greenhouse gas policy influences climate via direct effects of land-use change. *J. Clim.* 26, 3657–3670.
- Kaplan, J.O., Krumhardt, K.M., Zimmermann, N.E., 2012. The effects of land use and climate change on the carbon cycle of Europe over the past 500 years. *Global Change Biol.* 18, 902–914.
- Kastner, T., Schaffartzik, A., Eisenmenger, N., Erb, K.-H., Haberl, H., Krausmann, F., 2014. Cropland area embodied in international trade: contradictory results from different approaches. *Ecol. Econ.* 104, 140–144.
- Keys, E., McConnell, W.J., 2005. Global change and the intensification of agriculture in the tropics. *Global Environ. Change* 15, 320–337.
- Klein Goldewijk, K., Beusen, A., van Drecht, G., de Vos, M., 2011. The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Global Ecol. Biogeogr.* 20, 73–86.
- Krausmann, F., Erb, K.-H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzar, C., Searchinger, T.D., 2013. Global human appropriation of net primary production doubled in the 20th century. *Proc. Natl. Acad. Sci. U. S. A.* 110, 10324–10329.
- Kuemmerle, T., Erb, K., Meyfroidt, P., Müller, D., Verburg, P.H., Estel, S., Haberl, H., Hostert, P., Jepsen, M.R., Kastner, T., Levers, C., Lindner, M., Plutzar, C., Verkerk, P. J., van der Zanden, E.H., Reenberg, A., 2013. Challenges and opportunities in mapping land use intensity globally. *Curr. Opin. Environ. Sustain.* 5, 484–493.
- Kuemmerle, T., Olofsson, P., Chaskovskyy, O., Baumann, M., Ostapowicz, K., Woodcock, C.E., Houghton, R.A., Hostert, P., Keeton, W.S., Radeloff, V.C., 2011. Post-Soviet farmland abandonment, forest recovery, and carbon sequestration in western Ukraine. *Global Change Biol.* 17, 1335–1349.
- Lambin E.F., Baulais X, Bockstael NE, Fischer G, Krug T, Leemans R, Moran EF, Rindfuss RR, Sato Y, Skole D, Turner II BL, Vogel C 2000. Land-Use and Land-Cover Change (LUCC), Implementation Strategy. In: Stockholm, Bonn.
- Land-Use and Land-Cover Change—Local Processes and Global Impacts. In: Lambin, E.F., Geist, H. (Eds.), Springer, Berlin.
- Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. *Proc. Natl. Acad. Sci. U. S. A.* 108, 3465–3472.
- Le Quéré, C., Raupach, M.R., Canadell, J.G., Marland, G., Bopp, L., Ciais, P., Conway, T.J., Doney, S.C., Feely, R.A., Foster, P., 2009. Trends in the sources and sinks of carbon dioxide. *Nat. Geosci.* 2, 831–836.
- Liu, J., 2014. Forest sustainability in china and implications for a telecoupled world. *Asia Pacific Policy Stud.* 1, 230–250.
- Liu, J.Q., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., Hertel, T.W., Izaurralde, R. C., Lambin, E.F., Li, S., Martinelli, L.A., McConnell, W., Moran, E.F., Naylor, R., Ouyang, Z., Polenske, K.R., Reenberg, A., de Miranda Rocha, G., Simmons, C.S., Verburg, P.H., Vitousek, P.M., Zhang, F., Zhu, C., 2013. Framing sustainability in a telecoupled world. *Ecol. Soc.* 18(6) 2.
- Lotze-Campen, H., Popp, A., Beringer, T., Müller, C., Bondeau, A., Rost, S., Lucht, W., 2010. Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade. *Ecol. Model.* 221, 2188–2196.
- Luyssaert, S., Jammot, M., Stoy, P.C., Estel, S., Pongratz, J., Ceschia, E., Churkina, G., Don, A., Erb, K., Ferlicoq, M., 2014. Land management and land-cover change have impacts of similar magnitude on surface temperature. *Nat. Clim. Change* 4, 389–393.
- Magliocca, N., Rudel, T., Verburg, P., McConnell, W., Mertz, O., Gerstner, K., Heinimann, A., Ellis, E., 2014. Synthesis in land change science: methodological patterns, challenges, and guidelines. *Reg. Environ. Change* 15, 211–226.
- Mahmood, R., Pielke, R.A., Hubbard, K.G., Niyogi, D., Dirmeyer, P.A., McAlpine, C., Carleton, A.M., Hale, R., Gameda, S., Beltrán-Przekurat, A., 2014. Land cover changes and their biogeophysical effects on climate. *Int. J. Climatol.* 34, 929–953.
- Margulis, M.E., McKeon, N., Borras, S.M., 2013. Land grabbing and global governance: critical perspectives. *Globalizations* 10, 1–23.
- Matson, P.A., Vitousek, P.M., 2006. Agricultural intensification: will land spared from farming be land spared for nature? *Conserv. Biol.* 20, 709–710.

- Matthews, R., Gilbert, N., Roach, A., Polhill, J., Gotts, N., 2007. Agent-based land-use models: a review of applications. *Landscape Ecol.* 22, 1447–1459.
- McMichael, P., 2012. The land grab and corporate food regime restructuring. *The Journal of Peasant Studies* 39, 681–701.
- Mertz, O., Mbow, C., Nielsen, J.O., Maiga, A., Diallo, D., Reenberg, A., Diouf, A., Barbier, B., Moussa, I.B., Zorom, M., Ouattara, I., Dabi, D., 2010. Climate factors play a limited role for past adaptation strategies in West Africa. *Ecol. Soc.* 15.
- Messerli, P., Giger, M., Dwyer, M.B., Breu, T., Eckert, S., 2014. The geography of large-scale land acquisitions: analysing socio-ecological patterns of target contexts in the global South. *Appl. Geogr.* 53, 449–459.
- Meyfroidt, P., Lambin, E.F., 2009. Forest transition in Vietnam and displacement of deforestation abroad. *Proc. Natl. Acad. Sci. U. S. A.* 106, 16139–16144.
- Meyfroidt, P., Rudel, T.K., Lambin, E.F., 2010. Forest transitions, trade, and the global displacement of land use. *Proc. Natl. Acad. Sci. U. S. A.* 107, 20917–20922.
- Muradian, R., Corbera, E., Pascual, U., Kosoy, N., May, P.H., 2010. Reconciling theory and practice: An alternative conceptual framework for understanding payments for environmental services. *Ecol. Econ.* 69, 1202–1208.
- Nagendra, H., Reyers, B., Lavorel, S., 2013a. Impacts of land change on biodiversity: making the link to ecosystem services. *Curr. Opin. Environ. Sustain.* 5, 503–508.
- Nagendra, H., Sudhira, H.S., Katti, M., Schewenius, M., 2013b. Sub-regional assessment of India: effects of urbanization on land use, biodiversity and ecosystem services. In: Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J., McDonald, R.I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K.C., Wilkinson, C. (Eds.), *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities*. Springer, Netherlands, pp. 65–74.
- Nagendra, H., Unnikrishnan, H., Sen, S., 2013c. Villages in the city: spatial and temporal heterogeneity in rurality and urbanity in Bangalore, India. *Land* 3, 1–18.
- National Research Council, 2013. *Advancing Land Change Modeling: Opportunities and Research Requirements* (committee members: Brown, D., Band, L.E., Green, K.O., Irwin, E.G., Jain, A., Lambin, E.F., Pontius, R.G., Seto, K.C., Turner, II B.L., Verburg, P.H.). The National Academies Press.
- Peluso, N.L., Lund, C., 2011. New frontiers of land control: introduction. *J. Peasant Stud.* 38, 667–681.
- Pereira, H.M., Leadley, P.W., Proenca, V., Alkemade, R., Scharlemann, J.P.W., Fernandez-Manjarres, J.F., Araujo, M.B., Balvanera, P., Biggs, R., Cheung, W.W.L., Chini, L., Cooper, H.D., Gilman, E.L., Guenette, S., Hurr, G.C., Huntington, H.P., Mace, G.M., Oberdorff, T., Revenga, C., Rodrigues, P., Scholes, R.J., Sumaila, U.R., Walpole, M., 2010. Scenarios for global biodiversity in the 21st century. *Science* 330, 1496–1501.
- Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. *Science* 333, 1289–1291.
- Pitelka, L., Canadell, J., Pataki, D., 2007. Global Ecology, Networks, and Research Synthesis. In: Canadell, J., Pataki, D., Pitelka, L. (Eds.), *Terrestrial Ecosystems in a Changing World*. Springer, Berlin, Heidelberg, pp. 1–5.
- Pitman, A.J., de Noblet-Ducoudré, N., Cruz, F.T., Davin, E.L., Bonan, G.B., Brovkin, V., Claussen, M., Delire, C., Ganzeveld, L., Gayler, V., van den Hurk, B.J.J.M., Lawrence, P.J., van der Molen, M.K., Müller, C., Reick, C.H., Seneviratne, S.I., Strengers, B.J., Voldoire, A., 2009. Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study. *Geophys. Res. Lett.* 36.
- Pongratz, J., Raddatz, T., Reick, C.H., Esch, M., Claussen, M., 2009. Radiative forcing from anthropogenic land cover change since AD 800. *Geophys. Res. Lett.* 36.
- Pontius, R.G., Cornell, J.D., Hall, C.A.S., 2001. Modeling the spatial pattern of land-use change with GEOMOD2: application and validation for Costa Rica. *Agric. Ecosyst. Environ.* 85, 191–203.
- Priess, J.A., Schaldach, R., 2008. Integrated models of the land system: a review of modelling approaches on the regional to global scale. *Living Rev. Landscape Res.* 2.
- Prishchepov, A.V., Radeloff, V.C., Baumann, M., Kuemmerle, T., Müller, D., 2012. Effects of institutional changes on land use: agricultural land abandonment during the transition from state-command to market-driven economies in post-Soviet Eastern Europe. *Environ. Res. Lett.* 7, 024021.
- Qiang, W., Liu, A., Cheng, S., Kastner, T., Xie, G., 2013. Agricultural trade and virtual land use: the case of China's crop trade. *Land Use Policy* 33, 141–150.
- Reid, W.V., Chen, D., Goldfarb, L., Hackmann, H., Lee, Y.T., Mokhele, K., Ostrom, E., Raivio, K., Rockström, J., Schellnhuber, H.J., Whyte, A., 2010. Earth system science for global sustainability: grand challenges. *Science* 330, 916–917.
- Rindfuss, R.R., Walsh, S.J., Turner, B.L., Fox II, J., Mishra, V., 2004. Developing a science of land change: challenges and methodological issues. *Proc. Natl. Acad. Sci. U. S. A.* 101, 13976–13981.
- Rosegrant, M.W., Cline, S.A., 2003. *Global Food Security: Challenges and Policies*. Science 302, 1917–1919.
- Rounsevell, M.D.A., Arneth, A., Alexander, P., Brown, D.G., de Noblet-Ducoudré, N., Ellis, E., Finnigan, J., Galvin, K., Grigg, N., Harman, I., Lennox, J., Magliocca, N., Parker, D., O'Neill, B.C., Verburg, P.H., Young, O., 2014. Towards decision-based global land use models for improved understanding of the Earth system. *Earth Syst. Dynam.* 5, 117–137.
- Rounsevell, M.D.A., Robinson, D.T., Murray-Rust, D., 2012. From actors to agents in socio-ecological systems models. *Philos. Trans. R. Soc. B* 367, 259–269.
- Roy, D.P., Wulder, M.A., Loveland, T.R.C.E., W. Allen R.G., Anderson, M.C., Helder, D., Irons, J.R., Johnson, D.M., Kennedy, R., Scambos, T.A., Schaaf, C.B., Schott, J.R., Sheng, Y., Vermote, E.F., Belward, A.S., Bindaschadler, R., Cohen, W.B., Gao, F., Hipple, J.D., Hostert, P., Huntington, J., Justice, C.O., Kilic, A., Kovalsky, V., Lee, Z. P., Lymburner, L., Masek, J.G., McCorkel, J., Shuai, Y., Trezza, R., Vogelmann, J., Wynne, R.H., Zhu, Z., 2014. Landsat-8: science and product vision for terrestrial global change research. *Remote Sens. Environ.* 145, 154–172.
- Rudel, T.K., 2008. Meta-analyses of case studies: a method for studying regional and global environmental change. *Global Environ. Change* 18, 18–25.
- Schönweger, O., Heinemann, A., Epprecht, M., Lu, J., Thalongsengchanh, P., 2012. Concessions and leases in the Lao PDR: taking stock of land investments. *Geographica Bernensia*. Bern and Vientiane: Centre for Development and Environment (CDE). University of Bern, pp. 98.
- Seppelt, R., Lautenbach, S., Volk, M., 2013. Identifying trade-offs between ecosystem services, land use, and biodiversity: a plea for combining scenario analysis and optimization on different spatial scales. *Curr. Opin. Environ. Sustain.* 5, 458–463.
- Serna-Chavez, H.M., Schulp, C.J.E., van Bodegom, P.M., Bouten, W., Verburg, P.H., Davidson, M.D., 2014. A quantitative framework for assessing spatial flows of ecosystem services. *Ecol. Indic.* 39, 24–33.
- Seto, K.C., Fragkias, M., Güneralp, B., Reilly, M.K., 2011. A meta-analysis of global urban land expansion. *PLoS One* 6, e23777.
- Seto, K.C., Reenberg, A. (Eds.), 2014. *Rethinking Global Land Use in an Urban Era*. MIT Press, Cambridge, MA.
- Seto, K.C., Reenberg, A., Boone, C.G., Fragkias, M., Haase, D., Langanke, T., Marcotullio, P., Munroe, D.K., Olah, B., Simon, D., 2012. Urban land teleconnections and sustainability. *Proc. Natl. Acad. Sci. U. S. A.*
- Sikor, T., Auld, G., Bebbington, A.J., Benjaminsen, T.A., Gentry, B.S., Hunsberger, C., Izac, A.-M., Margulis, M.E., Plieninger, T., Schroeder, H., Upton, C., 2013. Global land governance: from territory to flow? *Curr. Opin. Environ. Sustain.* 5, 522–527.
- Sikor, T., Müller, D., 2009. The limits of state-led land reform: an introduction. *World Dev.* 37, 1307–1316.
- Sikor, T., Stahl, J., 2011. Introduction: the rights agenda in international forestry. In: Sikor, T., Stahl, J. (Eds.), *Forests and Peoples: Property, Governance and Human Rights*. Earthscan, London.
- Sleeter, B.M., Sohl, T.L., Bouchard, M.A., Reker, R.R., Soular, C.E., Acevedo, W., Griffith, G.E., Sleeter, R.R., Auch, R.F., Sayler, K.L., Pringle, S., Zhu, Z., 2012. Scenarios of land use and land cover change in the conterminous United States: utilizing the special report on emission scenarios at ecoregional scales. *Global Environ. Change* 22, 896–914.
- Smajgl, A., Brown, D.G., Valbuena, D., Huigen, M.G.A., 2011. Empirical characterisation of agent behaviours in socio-ecological systems. *Environ. Model. Software* 26, 837–844.
- Smith, P., Ashmore, M.R., Black, H.I.J., Burgess, P.J., Evans, C.D., Quine, T.A., Thomson, A.M., Hicks, K., Orr, H.G., 2013. REVIEW: the role of ecosystems and their management in regulating climate, and soil, water and air quality. *J. Appl. Ecol.* 50, 812–829.
- Steinfeld, H., Gerber, P., Wassenaar, T.D., Castel, V., Food, Nations AootU, Livestock, E., Development, de Haan, C., 2006. *Livestock's Long Shadow: Environmental Issues and Options*. Food and Agriculture Organization of the United Nations.
- Stocker, B.D., Feissli, F., Strassmann, K.M., Spahni, R., Joos, F., 2014. Past and future carbon fluxes from land use change, shifting cultivation and wood harvest. *Tellus* 66.
- Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J., Whitbread, A., 2012. Global food security, biodiversity conservation and the future of agricultural intensification. *Biol. Conserv.* 151, 53–59.
- Turner, B.L., Lambin, E.F., Reenberg, A., 2007. The emergence of land change science for global environmental change and sustainability. *Proc. Natl. Acad. Sci. U. S. A.* 104, 20666–20671.
- Turner II, B.L., Janetos, A.C., Verburg, P.H., Murray, A.T., 2013. Land system architecture: using land systems to adapt and mitigate global environmental change. *Global Environ. Change* 23, 395–397.
- Turner II, B.L., Ross, R.H., Skole, D.L., 1993. Relating land use and global land-cover change: a proposal for an IGBP-HDP core project. Report from the IGBP-HDP working group on land-use/land-cover change. Joint publication of the International Geosphere-Biosphere Programme (Report No. 24) and the Human Dimensions of Global Environmental Change Programme (Report No. 5). Royal Swedish Academy of Sciences, Stockholm.
- United Nations, 2010. *World Urbanization Prospects: The 2009 Revision* (United Nations Department of Economic and Social Affairs/Population Division, New York). <http://esa.un.org/unpd/wup/index.htm>.
- Van Asselen, S., Verburg, P.H., Vermaat, J.E., Janse, J., 2013. A global meta-analysis of wetland conversion. *PLoS One* 8, e81292.
- van Vliet, J., Magliocca, N., Büchner, B., Cook, E., Rey Benayas, J., Ellis, E., Heinemann, A., Keys, E., Lee, T., Liu, J., Mertz, O., Meyfroidt, P., Moritz, M., Poeplau, C., Robinson, B., Seppelt, R., Seto, K., Verburg, P., 2015. Meta-studies in land use science: current coverage and prospects. *Ambio* 015–s13280 (in press).
- van Vliet, N., Mertz, O., Heinemann, A., Langanke, T., Pascual, U., Schmoock, B., Adams, C., Schmidt-Vogt, D., Messerli, P., Leisz, S., Castella, J.C., Jörgensen, L., Birch-Thomsen, T., Hett, C., Bech-Bruun, T., Ickowitz, A., Vu, K.C., Yasuyuki, K., Fox, J., Padoch, C., Dressler, W., Ziegler, A.D., 2012. Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: a global assessment. *Global Environ. Change* 22, 418–429.
- Verburg, P., van Berkel, D., van Doorn, A., van Eupen, M., van den Heiligenberg, H., 2010. Trajectories of land use change in Europe: a model-based exploration of rural futures. *Landscape Ecol.* 25, 217–232.
- Verburg, P.H., 2006. Simulating feedbacks in land use and land cover change models. *Landscape Ecol.* 21, 1171–1183.

- Verburg, P.H., Dearing, J., Dyke, J., Leeuw, S.V.D., Seitzinger, Steffen, W., Syvitski, J., 2015. Methods and approaches to modelling the anthropocene. *Global Environ. Change* doi:<http://dx.doi.org/10.1016/j.gloenvcha.2015.08.007>.
- Verburg, P.H., Denier van der Gon, H.A.C., 2001. Spatial and temporal dynamics of methane emissions from agricultural sources in China. *Global Change Biol.* 7, 31–47.
- Verburg, P.H., Eickhout, B., van Meijl, H., 2008. A multi-scale, multi-model approach for analyzing the future dynamics of European land use. *Ann. Reg. Sci.* 42, 57–77.
- Verburg, P.H., Erb, K.-H., Mertz, O., Espindola, G., 2013. Land System Science: between global challenges and local realities. *Curr. Opin. Environ. Sustain.* 5, 433–437.
- Verburg, P.H., Neumann, K., Nol, L., 2011. Challenges in using land use and land cover data for global change studies. *Global Change Biol.* 17, 974–989.
- Verburg, P.H., Schot, P., Dijst, M., Veldkamp, A., 2004. Land use change modelling: current practice and research priorities. *GeoJournal* 61, 309–324.
- Verburg, P.H., Veldkamp, A., de Koning, G.H.J., Kok, K., Bouma, J., 1999. A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. *Ecol. Model.* 116, 45–61.
- Walsh, S.J., Crews-Meyer, K.A., 2002. *Linking People, Place, and Policy: A GIScience Approach*. Kluwer Academic Publishers, Boston.
- Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A., 2013. Affluence drives the global displacement of land use. *Global Environ. Change* 23, 433–438.
- White, B., Borras, Jr SM, Hall, R., Scoones, I., Wolford, W., 2012. The new enclosures: critical perspectives on corporate land deals. *J. Peasant Stud.* 39, 619–647.
- Wolff, S., Schulp, C.J.E., Verburg, P.H., 2015. Mapping ecosystem services demand: a review of current research and future perspectives. *Ecol. Indic.* 55, 159–171.
- Wu, J., 2013a. Key concepts and research topics in landscape ecology revisited: 30 years after the Allerton Park workshop. *Landscape Ecol.* 28, 1–11.
- Wu, J., 2013b. Landscape sustainability science: ecosystem services and human well-being in changing landscapes. *Landscape Ecol.* 28, 999–1023.
- Yu, Y., Feng, K., Hubacek, K., 2013. Tele-connecting local consumption to global land use. *Global Environ. Change* 23, 1178–1186.
- Zaehle, S., Ciais, P., Friend, A.D., Prieur, V., 2011. Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions. *Nat. Geosci.* 4, 601–605. doi:<http://dx.doi.org/10.1038/ngeo1207>.
- Zalasiewicz, J., Crutzen, P.J., Steffen, W., 2012. Chapter 32—the anthropocene. In: Gradstein, F.M., Schmitz, J.G.O.D., Ogg, G.M. (Eds.), *The Geologic Time Scale*. Elsevier, Boston, pp. 1033–1040.
- Ziegler, A.D., Phelps, J., Yuen, J.Q.I., Webb, E.L., Lawrence, D., Fox, J.M., Bruun, T.B., Leisz, S.J., Ryan, C.M., Dressler, W., Mertz, O., Pascual, U., Padoch, C., Koh, L.P., 2012. Carbon outcomes of major land-cover transitions in SE Asia: great uncertainties and REDD+ policy implications. *Global Change Biol.* 18, 3087–3099.